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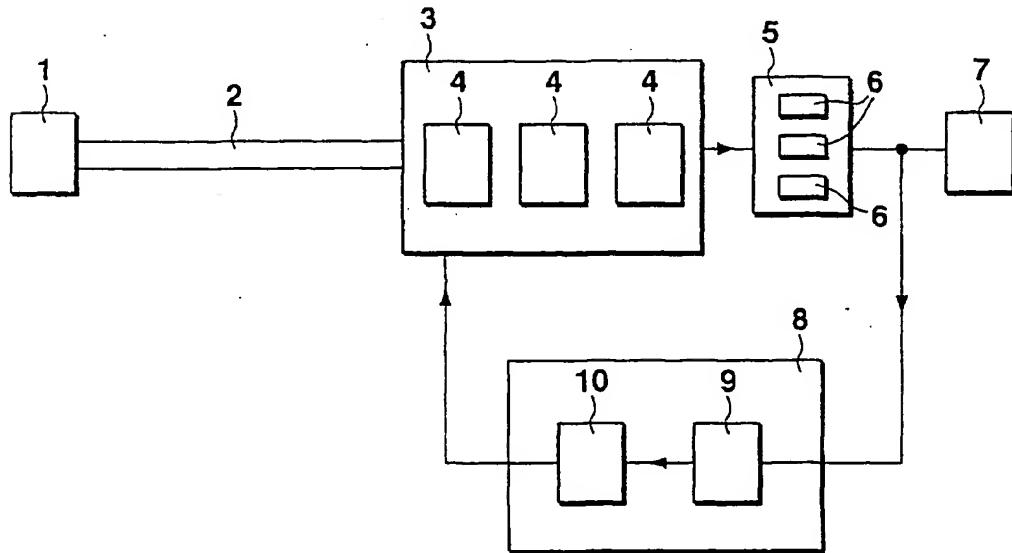
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## (54) Compensation of polarization mode dispersion

(57) A method and a device for compensating the polarization mode dispersion (PMD) of a transmitted optical signal comprise means of a polarization controller (3) coupled to a differential group delay (DGD) generator (5). The polarization controller (3) is controlled by a feedback loop, said feedback loop implementing an op-

timisation algorithm to optimize a feedback parameter of the output signal of the DGD generator (5). The algorithm takes into account the state of polarization (SOP) of an optical signal determined from the output signal of the polarization controller (3) or from the output signal from the DGD generator (5).

Fig. 1



**Description**

[0001] The invention relates to a method and a device for compensating the polarization mode dispersion (PMD) of a transmitted optical signal by means of a polarization controller coupled to a differential group delay generator, whereby the polarization controller is controlled by a feedback signal computed by a control algorithm.

**State of the art**

[0002] A method and a device of this type are known in the art through EP-0 853 395.

[0003] All types of fiber links present the phenomenon of polarization mode dispersion, i.e. the impulse or signal emitted by an emitter terminal and transmitted via a fiber link is received in a deformed state by a receiver terminal. It shows a longer duration than its original duration. This deformation is due to the fact that the optical signal depolarizes during transmission. The signal received at the other end of the fiber link can be considered as two perpendicular components, where one corresponds to a state of polarization (SOP) with maximum propagation velocity and the other corresponds to an SOP with minimum propagation velocity. In other words, the signal received at the other end of the fiber link can be considered as being constituted by a first signal polarized with a privileged SOP arriving first and a second signal propagating with a second delayed SOP arriving with a delay called differential group delay, which depends in particular on the length of the fiber link.

[0004] If the emitter terminal emits an optical signal with a very short impulse, the optical signal received by the receiver terminal consists of two successive impulses polarized perpendicular to one another and having a time delay corresponding to the differential group delay. This delay can be in the order of 20 picoseconds for a link of 100 kilometers comprising a single mode fiber produced a few years ago. The deformation of the impulses received by the receiver terminal can cause errors in decoding the transmitted data, hence the polarization mode dispersion is a limiting factor for the performance of optical links, analog as well as digital.

[0005] Fibers with strong polarization mode dispersion, also called polarization maintaining fibers, are known, which allow supplying a fixed differential group delay by using short sections of fiber. Optical compensation of the polarization mode dispersion can be realized by disposing such a component, or a whole differential group delay generator, between two perpendicular polarization modes which result from a fiber link with strong polarization mode dispersion. This can be implemented either by using a polarization maintaining fibre (PMF) with the same differential group delay as the fiber link, but by exchanging the slow and fast principle SOPs, or by forcing a principle SOP of the system consisting of the fiber link and the PMF to coincide with the SOP

of the source of emission. In order to do this, a polarization controller is placed between the fiber link and the PMF.

[0006] The value of the differential group delay and the principle SOPs of a link vary over time with temperature and vibrations. A compensation means must therefore be adaptive and the differential group delay of the PMF must be chosen such that it is at least equal to all the values of differential delay that are to be compensated.

[0007] Such a means for compensating the PMD in a system of optical transmission became known by the EP 0853 395 A1. The means comprises a polarization controller and a differential group delay generator. The controller and the generator are disposed between the fiber link and the receiver terminal. A feedback loop measures the degree of polarization (DOP) of the optical signal delivered by the DGD generator and feeds the polarization controller such that the DOP measured is optimized. However, using the DOP as feedback variable requires a complicated algorithm for computing the control of the polarization controller. Furthermore, the re-winding of birefringent elements in the polarization controller constitutes a major problem.

**Object of the invention**

[0008] The object of the present invention is therefore to provide a method and a device for a faster and more accurate control of the polarization controller.

**Teaching of the invention**

[0009] In a first aspect of the invention, the problem is solved by a method and a device for compensating the polarization mode dispersion (PMD) of a transmitted optical signal by means of a polarization controller coupled to a differential group delay (DGD) generator, whereby the polarization controller is controlled by a feedback loop, said feedback loop implementing an optimisation algorithm to optimize a feedback parameter of the output signal of the DGD generator. The algorithm takes into account the state of polarization (SOP) of an optical signal determined from the output signal of the polarization controller or from the output signal of the DGD generator. The feedback parameter can be the DOP, or a measure of the electrical spectral width, or a measure of the eye opening, etc. Preferably it is the DOP, as the measurement procedure is common. If the feedback parameter used is the DOP, it is more practical to measure it at the output of the DGD generator (since the same equipment is used), but the theory holds when it is measured at the input of it.

[0010] In a variant of the inventive method the SOP is computed from the Stokes parameters measured from the output signal of the DGD generator. For the feedback loop a very high speed is required. The Stokes parameters can be easily measured and from the meas-

ured values the position of the SOP on the Poincaré sphere can be easily computed. Hence the measurement of the Stokes parameters is particularly suitable for a fast and accurate feedback to the polarization controller. The control signals computed by the algorithm are fed back to the polarization controller. Measurement of the Stokes parameters allows to make the algorithm easier and faster. Thus the processing of high bit rates becomes possible in single mode fiber links.

[0011] In a preferred variant of the method the polarization controller comprises at least one birefringent element and for each birefringent element an angle  $\alpha$  is fixed and a rotation angle  $\beta$  is variable, where the angle  $\alpha$  is the angle between a rotation axis on the equatorial plane of the Poincaré sphere and the x-axis of a coordinate system and the rotation angle  $\beta$  defines the rotation around the rotation axis. A birefringent element changes the SOP at its input into another SOP at its output by a rotation of the SOP on the Poincaré sphere.

[0012] A polarization controller consists of a cascade of birefringent elements with either a variable  $\alpha$  or a variable  $\beta$ , or both. If a birefringent element is to allow a variable  $\beta$ , the birefringent element must be wound back once the maximum  $\beta$  is reached since it cannot reach infinite values and other birefringent elements would have to compensate for this element. The rewinding process requires a complicated algorithm. In contrast, if the angle  $\alpha$  is variable and  $\beta$  is fixed, the complicated rewinding process of the birefringent elements can be facilitated or even avoided.

[0013] Advantageously, the impact of each birefringent element on the position of the SOP on the Poincaré sphere is determined. If the position or the variation of the SOP on the Poincaré sphere is known, the algorithm in the feedback loop can take this into account and vary its step accordingly. The algorithm takes a larger step if the SOP is close to the rotation axis and a smaller step, when the SOP is further away from the rotation axis. In addition, knowing the variation of the SOP due to each birefringent element in the polarization controller allows to combine the birefringent elements such that the voltages applied to them and thus their position can be changed without changing the SOP. This increases the speed of the rewinding process. Determining the SOP and using it in the algorithm in the feedback loop could also be used with polarization controllers of the state of the art, i.e. where  $\beta$  is fixed and  $\alpha$  is variable.

[0014] In a preferred embodiment of the inventive device, the polarization controller comprises at least one birefringent element. The control signals determined by the algorithm in the feedback loop are fed back to the polarization controller and the positions of the birefringent elements in the polarization controller are adjusted in order to compensate for PMD by maximizing the DOP. The constraints on the birefringent elements can be relaxed by use of the inventive device since the algorithm required to compensate for imperfections of the birefringent elements becomes less complicated.

[0015] Preferably, the DGD generator comprises at least one polarization maintaining fibre (PMF). The polarization maintaining fiber compensates for the differential group delay resulting from the fiber link by launching the fast signal part into the slow eigenstate of a polarization maintaining high birefringent fiber and vice versa.

#### Drawing

[0016] Additional advantages of the invention can be gathered from the description and the drawing. Also, the previously mentioned and the following characteristics can be used according to the invention each individually, or collectively in any combination. The embodiments shown and described are not to be taken as a conclusive enumeration, but have exemplary character for the description of the invention. It shows:

[20] Fig. 1 a schematic representation of an optical communications system comprising an inventive device for the compensation of polarization mode dispersion.

[25] Fig. 2 a representation of the state of polarization in the Poincaré sphere.

#### Description of an embodiment

[30] [0017] In Fig. 1 the numeral 1 denotes an emitter terminal transmitting data as an optical signal, for example by modulating the intensity of one or several completely polarized optical carrier waves supplied by a laser. This optical signal is fed into a fiber link 2 connected to a polarization controller 3. The polarization controller 3 comprises several cascaded birefringent elements 4 for controlling the state of polarization (SOP). The polarization controller 3 is used for turning the angle of polarization of all the components of the optical signal received by the polarization controller 3. A differential group delay (DGD) generator 5 is disposed downstream from the polarization controller 3. The DGD generator 5 comprises polarization maintaining fibers 6 (PMF) of different lengths for compensating the differential delay resulting from the fiber link 2.

[0018] The optical output signal from the DGD generator 5 is transmitted to a receiver terminal 7 and a feedback loop 8. The feedback loop has a means 9 for measuring the Stokes parameters of the output signal of the DGD generator and a computing unit 10 calculating the control signal for the polarization controller 3 taking into account the Stokes parameters measured by the means 9.

[0019] Fig. 2 shows a representation of the state of polarization (SOP), for example A, in the Poincaré sphere 20. The Poincaré sphere 20 represents all the transitional states unpolarized light can assume with equal probability. In Fig. 2 a unit sphere (radius = 1) is

drawn with a system of coordinates, the origin 21 of which lies in the center of the Poincaré sphere 20. A birefringent element 4 changes the SOP A, A', A" at its input into another SOP at its output B, B', B" by a rotation of the SOP on the Poincaré sphere 20. The position on the Poincaré sphere 20 of an SOP B, B', B" of polarized light is defined by an angle  $\alpha$  between the x-axis 22 of the system of coordinates and a rotation axis 23, and an angle  $\beta$  between the equatorial plane 24 of the Poincaré sphere 20 and a line 25 connecting the SOP B, B', B" at the input and the rotation axis 23, with the line 25 being perpendicular to the rotation axis 23.

[0020] In Fig. 2 the angle  $\alpha$  is fixed and the angle  $\beta$  is variable. The SOPs A, A', A" at the input lie in this case all on the equator line of the Poincaré sphere. Each has a different distance to the rotation axis 23. When the birefringent element rotates the SOPs A, A', A" at the input by the angle  $\beta$  around the rotation axis 23, the SOPs B, B', B" result. If the distance of an SOP A, A', A" at the input to the rotation axis is large, the distance of the SOP B, B', B" at the output is also large. Thus, the algorithm in the feedback loop can adapt its step according to the distance of an input SOP A, A', A" from the rotation axis 23, i.e. a wider step when A, A', A" is close to the rotation axis and vice versa.

[0021] For a practical implementation of the algorithm and the measurement of the Stokes parameter the embodiment uses polarizers and photodiodes. An example of realization can be found in "Polarization measurement of signal and components", Agilent Technologies, Application Note 8509-1.

[0022] The rotation axis is determined locally by a small dithering of  $\beta$ . From the measured SOP, the rotation matrix can be obtained. The computation of the rotation axis will take into account the theory developed in "Polarization control for coherent communications", N. Walker et al., IEEE Journal of Lightwave Technology, vol.8, n3.

[0023] The algorithm operates as follows: Let us assume that the polarization controller in the PMD compensator is composed of four birefringent elements called cells. In a standard algorithm, the driving voltages of the cells are dithered one after the other. For each cell, the sequence is as follows:

- ◆ the voltage is increased by a fixed amount  $\Delta V$
- ◆ the feedback signal (DOP or other) is measured
- ◆ if the feedback signal increases, the voltage is increased again by  $\Delta V$  if not it is set back to the initial value
- ◆ the same procedure is repeated with a decreased voltage

[0024] Taking into account the invention, the algorithm can now dither the voltage with a variable step  $\Delta V$  leading to a constant angular step on the Poincaré sphere. For each cell, the rotation axis is determined locally. The voltage to be applied on the cell therefore de-

pends on the distance between the SOP and the rotation axis of the cell, and the target angular step. The main advantage is that the impact of each cell is quantitatively known: if the SOP is on the rotation axis of a cell, it is a waste of time to actuate this cell as it will have no effect on the polarization control.

[0025] In the case of a "rewinding", when the impact of each cell is formally known, it is possible to find the best combination of rotations that will bring us back to the initial SOP with reasonable voltages on the cells.

### Claims

1. Method for compensating the polarization mode dispersion (PMD) of a transmitted optical signal by means of a polarization controller (3) coupled to a differential group delay (DGD) generator (5), whereby the polarization controller (3) is controlled by a feedback loop, said feedback loop implementing an optimisation algorithm to optimize a feedback parameter of the output signal of the DGD generator (5), **characterised in that** the algorithm takes into account the state of polarization (SOP) of an optical signal determined from the output signal of the polarization controller (3) or from the output signal from the DGD generator (5).
2. Method according to claim 1, **characterised in that** the feedback parameter is the degree of polarization (DOP).
3. Method according to claim 1 or 2, **characterized in that** the SOP is computed from the Stokes parameters measured from the output signal of the DGD generator (5).
4. Method according to any of the preceding claims, **characterized in that** the polarization controller (3) comprises at least one birefringent element (4) and for each birefringent element (4) an angle  $\alpha$  is fixed and a rotation angle  $\beta$  is variable, where the angle  $\alpha$  is the angle between a rotation axis (23) on the equatorial plane (24) of the Poincaré sphere (20) and the x-axis (22) of a coordinate system and the rotation angle  $\beta$  defines the rotation around the rotation axis (23).
5. Method according to any of the preceding claims, **characterized in that** the impact of each birefringent element (4) on the position of the SOP on the Poincaré sphere (20) is determined.
6. Device for compensating the polarization mode dispersion (PMD) of a transmitted optical signal comprising a polarization controller (3) coupled to a differential group delay (DGD) generator (5) whereby the polarization controller (3) is controlled by a feed-

back loop, said feedback loop implementing an optimisation algorithm to optimize a feedback parameter of the output signal of the DGD generator (5),, **characterized in that** the feedback loop (8) comprises means (9) for measuring the state of polarization (SOP) determined from the output signal of the polarization controller (3) or from the output signal from the DGD generator (5) and a computing unit (10) implementing an optimization algorithm, the steps thereof depending on the SOP.

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7. Device according to claim 6, **characterized in that** the SOP is computed from the Stokes parameters measured from the output signal of the DGD generator (5).

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8. Device according to claim 5, **characterized in that** the polarization controller (3) comprises at least one birefringent element (4).

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9. Device according to claim 5 or 6, **characterized in that** the DGD generator (5) comprises at least one polarization maintaining fibre (6) (PMF).

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Fig. 1

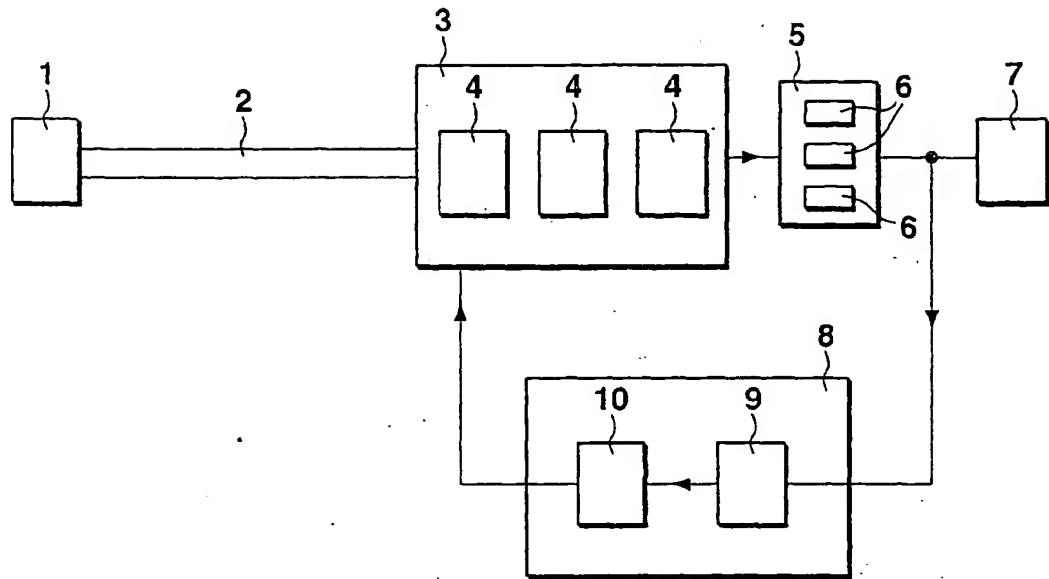
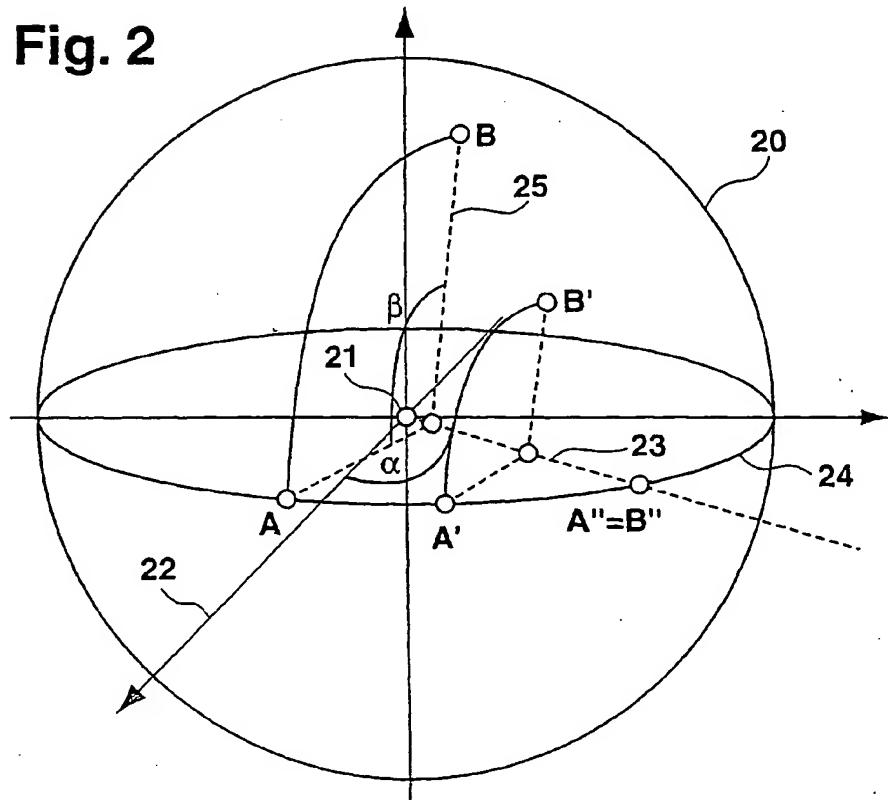


Fig. 2





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## EUROPEAN SEARCH REPORT

Application Number

EP 00 40 1942

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Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	
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Y	* abstract * * column 9, line 7 - line 28 * * figures 1,3 *	3-5,7,8	
Y	JOHNSON M ET AL: "REMOTE STATE-OF-POLARIZATION CONTROL IN POLARIZATION-MAINTAINING FIBRE" OPTICS COMMUNICATIONS, NL, NORTH-HOLLAND PUBLISHING CO. AMSTERDAM, vol. 90, no. 1 / 02 / 03, 1 June 1992 (1992-06-01), pages 32-34, XP000274833 ISSN: 0030-4018 * page 32, column 1, line 1 - line 3 * * page 33, column 1, line 35 - line 40 * * figure 2 *	3-5,7,8	
A	EP 0 909 045 A (LUCENT TECHNOLOGIES INC) 14 April 1999 (1999-04-14) * page 5, line 42 - line 51 * * page 6, line 53 - line 57 * * figure 1 *	1,2,6	TECHNICAL FIELDS SEARCHED (Int.Cl.) H04B
The present search report has been drawn up for all claims			
Place of search  THE HAGUE	Date of completion of the search  19 December 2000	Examiner  Reville, L	
CATEGORY OF CITED DOCUMENTS		T : theory or principle underlying the invention E : earlier patent document, but published on, or after the filing date D : document cited in the application L : document cited for other reasons & : member of the same patent family, corresponding document	
X : particularly relevant if taken alone Y : particularly relevant if combined with another document of the same category A : technological background C : non-patent disclosure P : intermediate document			

**ANNEX TO THE EUROPEAN SEARCH REPORT  
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This annex lists the patent family members relating to the patent documents cited in the above-mentioned European search report.  
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